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An indirect method for the quantitative identification of unstable rock

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Abstract: Under the influence of continuous external factors (rainfall, earthquake, construction, etc.), the slope rock mass in a stable state gradually transited to an unstable rock, and then the unstable rock collapsed. However, a safety factor can identify the occurrence of failure but cannot identify the transition of stable rock to unstable rock; thus, it cannot realise the quantitative identification of unstable rocks. In this study, safety factor of adhesion (SFA) and a relatively objective analysis method are proposed to effectively identify unstable rocks. SFA can be calculated by natural vibration frequency and applied as a mechanical index to judge unstable rock. When SFA is less than 1, the rock is defined as an unstable rock. Compared with the traditional method, the new method has the merits of simple operation, low cost and higher efficiency, and provides a relatively complete quantitative evaluation index and judgment criteria for quantitative identification of unstable rocks for engineers who are engaged in early warning and prevention of rock collapse.

Keywords: unstable rock, quantitative identification, natural vibration frequency, laser Doppler vibrometre (LDV), indirect method

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1 Introduction

Rock collapse is one of the most common geomorphic processes in hilly regions; it threatens the environment and generating loss of human life and property (Sun et al., 2017; Bunce et al. 1997). As referenced by Qiu (2016), a large number of slope rock masses will be in an unstable phase after earthquakes. Therefore, how to identify these unstable rocks is the main problem to be solved in engineering. During an earthquake, a rock mass is accompanied by real-time degradation of strength (Loew et al., 2017). Therefore, in the quick identification of unstable rocks, the analysis and judgment of the strength of rock bridge is the key (Fabre and Pellet 2006; Lalagüe et al., 2016; Xu et al., 2017).

Current research shows that the failure of unstable rock is an evolving dynamic process with the loss of rock bridge strength (Strom and Korup, 2006; Robinson et al., 2015; Du et al., 2019). In many forms and cases of damage to the rock bridges, such as strong earthquakes, long-term rainfall, or changes in environmental factors (e.g., a reservoir region), the rock becomes less stable and can be defined as an "unstable rock". Currently, the single safety factor can be used to effectively identify and analyse the stability of a rock during the failure stage, but identifying the state at which the rock becomes an unstable rock is difficult. These rocks often cause serious casualties and economic losses due to the lack of timely detection and management (Reder et al. 2017; Zhao et al. 2014). Therefore, determining how to apply relatively dynamic and practical safety factors in practical engineering and identifying the point at which a rock is in a weakened stability state is an urgent problem in geotechnical fields (Nasir and Fall, 2008; Nilsen. 2017).

Furthermore, the dynamic analysis of the rock bridge strength is the key (Fabre and Pellet 2006; Lalagüe et al., 2016; Xu et al., 2017). At present, the strength parameters are often determined based on relatively local in situ tests or relatively static experimental tests. However, this approach is often difficult to apply to unstable rocks with a wide distribution in mountainous areas. When the environmental conditions dramatically change, these methods cannot fully reflect the dynamic response of the rock and cannot satisfy the actual dynamic stability evaluation requirements of engineering (Du et al. 2015). Therefore, it is necessary to achieve low-cost and long-distance monitoring technology research on rock masses in these high-risk areas (Uehan and Minoura, 2015). As one of the remote technologies, Laser Doppler Vibrometer (LDV) can monitor natural vibration frequency of the rock mass, which can be used for indirect assessment for the strength of rock bridge (Uehan et al., 2012; Ma et al., 2015; Du et al., 2017b; Jia et al., 2019). Furthermore, the optical vibration measuring device has a simple structure, high precision, good accuracy, sensitivity and property of disturbance-proof, thus can be better applied to identify unstable rocks in mountainous areas. With the further improvement of the subsequent data processing process, the equipment will play an active role in rapid identification of unstable rocks. In the study, an indirect measurement of the rock bridge is introduced by using

natural vibration frequency, and a new method for quantitative identification of unstable rocks is presented. The improved method may solve the difficulty of investigation of unstable rocks, which can provide a reference for better response to rock collapse in engineering.

2 Methods

Fig. 1 Sketch of unstable rock

Figure 1 shows a schematic of unstable rock on the slope. In the study, the method introduced by Ma et al. (2015), which is expressed as Eq. (1), was adopted.

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \quad (1)$$

where f is the natural vibration frequency of the rock mass, M is the weight of the rock, and K is the equivalent stiffness of the rock bridge. Referenced by Babu et al. (2008), the stiffness can be described in terms of $K=ES/d$, where S , E and d are the bonding area, elastic modulus and thickness of the rock bridge, respectively. The natural vibration frequency is defined by Eq. (2):

$$f = \frac{1}{2\pi} \sqrt{\frac{ES}{Md}} \quad (2)$$

Based on Eq. (2), the bonding area of the rock mass at a certain time can be calculated from Eq. (3):

$$S_i = \frac{4\pi^2 Md}{E} f_i^2 \quad (3)$$

where S_i is the bonding area at a certain time and f_i is the natural vibration frequency of the rock mass at a certain time. Based on Eq. (3), when the initial S_0 and f_0 are known and other conditions remain unchanged, the bonding area S_i at a certain time can be calculated by Eq. (4):

$$S_i = \frac{S_0 f_i^2}{f_0^2} \quad (4)$$

It can be known from Eq. (4) that the fuzzy identification of the degree of bonding of the rock mass can be realised by monitoring the natural vibration frequency index.

As an important parameter in the stability analysis of rocks, the safety factor (SF) is the ratio of the anti-slip strength to the sliding force, which can be calculated from Eq. (5).

$$SF = \frac{cS + Mg \cos \alpha \tan \varphi}{Mg \sin \alpha} \quad (5)$$

where c is the adhesion of the slip surface, φ is the friction angle and α is the slope angle. As the ratio of the anti-slip strength to the sliding force, the stability analysis based on the safety factor may identify the rock collapse, but cannot identify unstable rocks. Here, we introduced a new factor to identify an unstable rock, which is referred to as the safety factor of adhesion (SFA).

SFA is the ratio of the bond strength to the shear stress of a rock on a potential slip surface, which can be calculated from Eq. (6).

$$SFA = \frac{cS}{Mg \sin \alpha} \quad (6)$$

where c is the adhesion force of the slip surface, and α is the slope angle. Compared with the traditional limit equilibrium method, SF_a is defined as the ratio of the cohesive force to the sliding force regardless of the effect of friction. Therefore, when SFA is greater than 1, the slip resistance of the slip surface is entirely provided by the cohesive force, and no downward trend exists. These conditions represent a stable rock. When SFA is less than 1, the cohesive force of the slip surface cannot fully satisfy the anti-slip requirements, and the rock exhibits a sliding trend, which is an unstable rock. Therefore, the calculation of SFA can effectively achieve an effective distinction between a stable rock and an unstable rock.

Based on Eqs. (4-6), SFA and SF at a certain time can be calculated from Eq. (7) and Eq. (8), respectively.

$$SF_i = \frac{cS_0 f_i^2 + Mgf_0^2 \cos \alpha \tan \varphi}{Mgf_0^2 \sin \alpha} \quad (7)$$

$$SFA_i = \frac{cS_0 f_i^2}{Mgf_0^2 \sin \alpha} \quad (8)$$

Based on SFA_i and SF_i , it is possible to effectively distinguish between stable rock and unstable rock and between unstable rock and rock failure, as shown in Table 1. The improved

method solves the difficulty of quantitative investigation of unstable rocks, thus can provide a reference for better response to rock collapse for engineers.

Table 1 Criteria for quantitative identification of unstable rocks

Phase	Type	SFA	SF
1	Stable rock	≥ 1	≥ 1
2	Unstable rock	< 1	≥ 1
3	Rock failure	< 1	< 1

3 Case study

Fig. 2 History curve of the safety factor

Consider experimental data as an example (DU et al. 2017a). The experiment is referred to as the “freeze-thaw test” (FTT). In this test, two toughened glass blocks are utilised: the upper glass represents the rock, and the lower glass represents the bedrock. The two blocks were placed in a freezer with a temperature of $-20\text{ }^{\circ}\text{C}$ for 48 h. After freezing, the blocks were positioned on top of each other, and the lower block was fastened to a slope. This thawing modelled the weakening of the strength parameters of the potential slide interface. When the safety factor decreased to less than “1”, the upper block slid. Fig. 2 shows the temporal curve of the safety factor. In the figure, SF decreases from 6.80 to 1.00, and then the block slides. The single safety factor can be used to determine the failure moment but cannot distinguish between stable rock and unstable rock. Additional coefficients, such as SFA , should be introduced to quantitatively evaluate the transformation from a stable rock to an unstable rock.

Fig. 3 History curves of the safety factor and safety factor of adhesion

According to Eq. (5), SFA could be calculated, as shown in Fig. 3.

When the rock is stable, the sliding resistance force is provided by the cohesive force. In this period, the rock is relatively stable. In this stage, SF decreases from 6.80 to 1.87, and SFA decreases from 5.85 to 1.00.

When the rock becomes unstable rock, the sliding resistance force is provided by the cohesive force and friction. In this period, the rock is unstable and dangerous. In this stage, SF decreases from 1.87 to 1.00, and SFA decreases from 1.00 to 0.09.

When the sliding resistance force provided by the cohesive force and friction cannot counteract the sliding force and the maximum level of static friction is reached, collapse occurs. At this moment, SF decreases below 1.00, and SFA decreases to below 0.09.

The improved method can provide a quantitative determination of when a stable rock becomes an unstable rock. Furthermore, the factors can be dynamic analysed without in-situ test, thus may help engineers perform a quantitative analysis of unstable rocks in high-risk regions.

4 Discussion

Many engineering experiences and accident cases show that collapse is mainly caused by potential sliding surface damage followed by the formation of dangerous rock mass and collapse failure. As the calculation of the safety factor can only identify the change from dangerous rock mass to collapse and it is not sensitive to the quantitative analysis evaluation and damage identification of stable rock to unstable rock, many limitations exist in engineering application (Du et al. 2015). For example, a large number of unstable rocks often cause serious casualties and economic losses due to the lack of timely detection and management in high-risk mountainous areas (Strom and Korup, 2006; Zhao et al. 2014; Robinson et al., 2015; Reder et al.

2017). Therefore, how to identify the point at which the rock becomes an unstable rock is an urgent problem in geotechnical fields (Nilsen. 2017). In order to compensate the shortcomings of traditional methods, we provide a simple and effective method to quantitative identify unstable rocks. Based on the dynamic stability evaluation model and the remote optical vibration monitoring technology, the improved method realizes the rapid identification of the unstable rock, as shown in Fig. 3. In the case study, we provide a new index (SFA) and a relatively objective analysis method. When a rock has no sliding trend, it can be defined as a stable rock. In this condition, SFA and SF are greater than 1. When the rock has a strong tendency to slide, the rock is deemed an "unstable rock". At this moment, SFA is less than 1, but SF is greater than 1. When SF decreases to less than 1, rock failure occurs, as shown in Table 1. The unified standard of judgment can compensate the shortcomings of traditional methods in the mechanical analysis of unstable rock identification to a certain extent.

Currently, remote optical vibration monitoring technology can be realised in advance by applying the new generation of laser transmitter. An increasing number of optical vibration measurement technologies, such as the LDV, are introduced to monitor these potentially dangerous rock masses on slopes (Du et al., 2016). Based on these technologies, the indirect quantitative evaluation of the length of rock bridge can be realised (Jia et al., 2019; Du et al., 2021), which provides a foundation for the rapid calculation of rock stability and quantitative identification of unstable rocks in high-risk mountainous areas.

According to Eq. (4), the values of S_0 and f_0 are needed for the calculation of S_i ; thus, we need to evaluate the bond area and monitor the natural vibration frequency of the rock mass in the initial stage. The objective of our work is to carry out detailed analysis and natural vibration frequency monitoring in the early stage. Therefore, on-site verification is not replaced but the work of field engineers will be greatly reduced. When a rock mass may be damaged by earthquake and heavy rain (Yin, et al., 2016; Kanari et al., 2019), engineers can calculate SFA to judge the rock stability instead of conducting in-situ tests and field investigations again. This approach can enable less time-consuming and labour-consuming on-site verification, thus can provide a reference for engineers who are engaged in rapid identifying unstable rocks. Since the merits of simple operation, low cost and higher efficiency, the improved method will provide technical support for the rapid stability assessment of unstable rocks, thus can enable a better investigation of unstable rocks in the high-risk mountainous areas.

5 Conclusion

Rapid recognition of unstable rocks has been a controversial issue in the study of geological hazards for many years. In this study, a new index (SFA) and a relatively objective analysis method are proposed to effectively identify unstable rocks. SFA can be calculated by natural vibration frequency and employed as a mechanical index to judge dangerous rock mass. When SFA is less than 1, the rock is defined as an unstable rock. The improved method can provide a

more reliable safety evaluation index and effective reference for engineers engaged in investigation of unstable rocks.

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Conflict of interest statement The authors declare that there is no conflict of interest in the manuscript.

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